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Title: Mo-100 Disk Structural Integrity Tests I

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Mo-100 Disk Structural Integrity Tests I

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Introduction

The NorthStar pressed and sintered 29 mm diameter, 0.5 mm thick Mo-100 disks will be subjected to large temperature gradients when in beam during production. The beam preferentially heats the disk center, while the aggressive cooling by the helium keeps areas outside the beam spot relatively cool. The result is a temperature gradient of up to 900°C over the radial distance of 14.5 mm. To test the disk integrity with this high temperature gradient, a special holder for a single disk was made such that proper cooling can be applied as in the design target and the disk heating can be replicated with induction heating. NorthStar press and sintered disks were used for these tests.

Setup

A single molybdenum disk was held in a stainless steel holder using shim stock material as specified by NorthStar design. The disk was held in place as shown in Figure 1. The shim stock was made from full hard SS 304 and has a nominal 29.26 mm diameter hole for the disk to remain captured. A GH Induction Atmospheres 30 kW induction heater was used to provide a high temperature (1000°C) elliptical shaped hot spot at the center of the disk. The incandescent hot spot has an overall width of ~15.6 mm and a height of ~18.6 mm. Note that this measurement is defined by the boundaries of emitted visible light (dull red) which begins at about 540°C and peaks at about 1000°C (yellow)[1] in these tests.

The induction coil can be seen in Fig. 2. At first, a non-contact Capacitec 520-XLC-4kHz displacement sensor calibrated at 1000°C was used to measure the displacement of the disk during heating and can be seen in Fig 3. However, the capacitance based sensor proved ineffective in this environment due to the induction heater coil, thus, the results were not trustworthy. Therefore, a new electrical component-free optical displacement sensor was used in place of the Capacitec sensor from this point forward. Specifically, a Keyence CL-3000 Series Confocal Displacement Sensor system was used with a CL-P070 Sensor Head and is shown in Fig 4. This sensor has a measurement range of 20 mm (±10 mm), a standoff distance of 70 mm at the midpoint, and a linearity of ±2.2 µm (±.000087”). Since the nominal standoff distance is nearly 2.75”, the sensor head does not need to be rated to 1000°C like the Capacitec sensor. Figure 5 shows a top down view of the Keyence displacement sensor head, disk holder assembly, and induction heater coil.

[1] T. Digges and S. Rosenberg, Heat Treatment and Properties of Iron and Steel, p. 22, Oct 1960

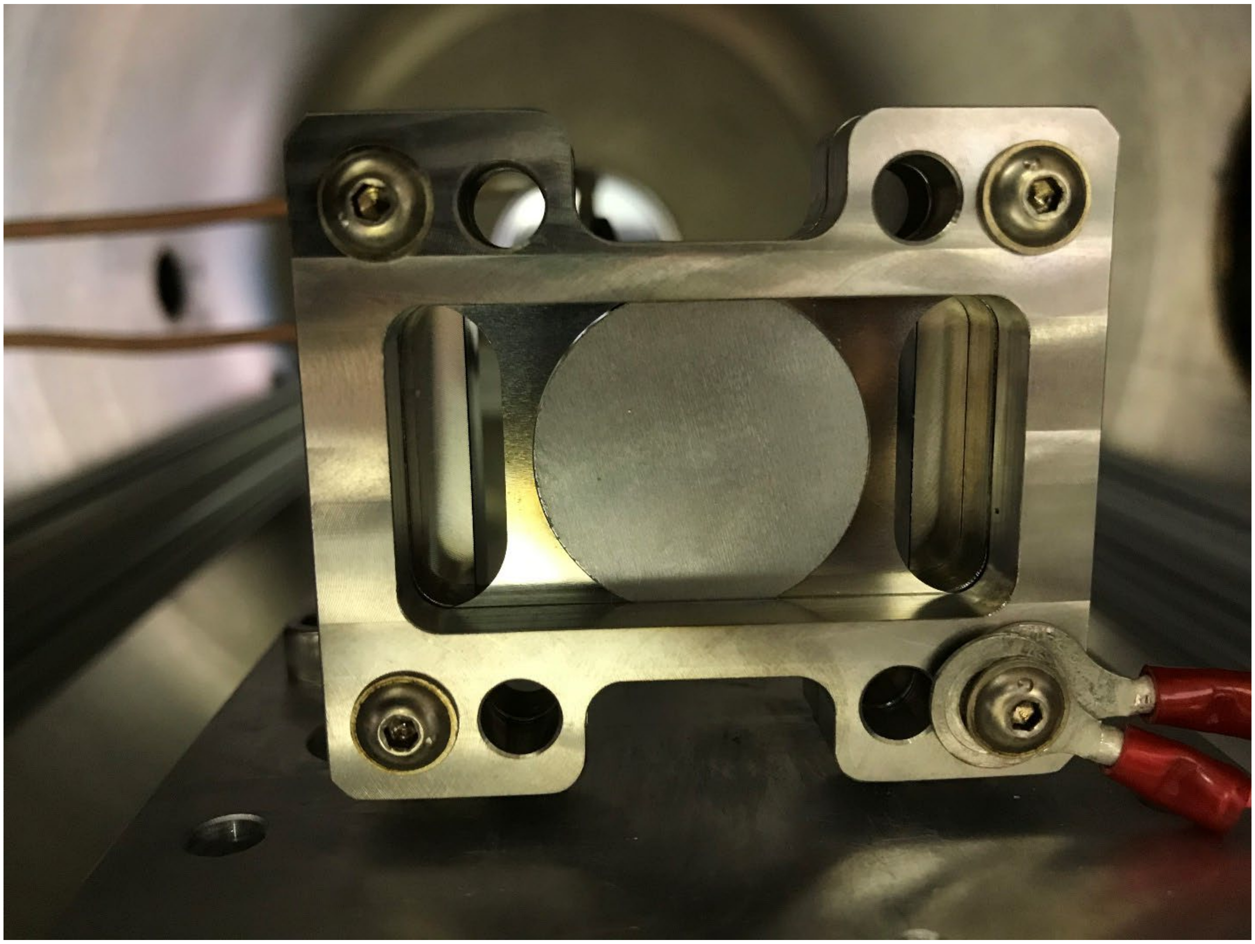

Figure 1 - Molybdenum disk in single disk holder

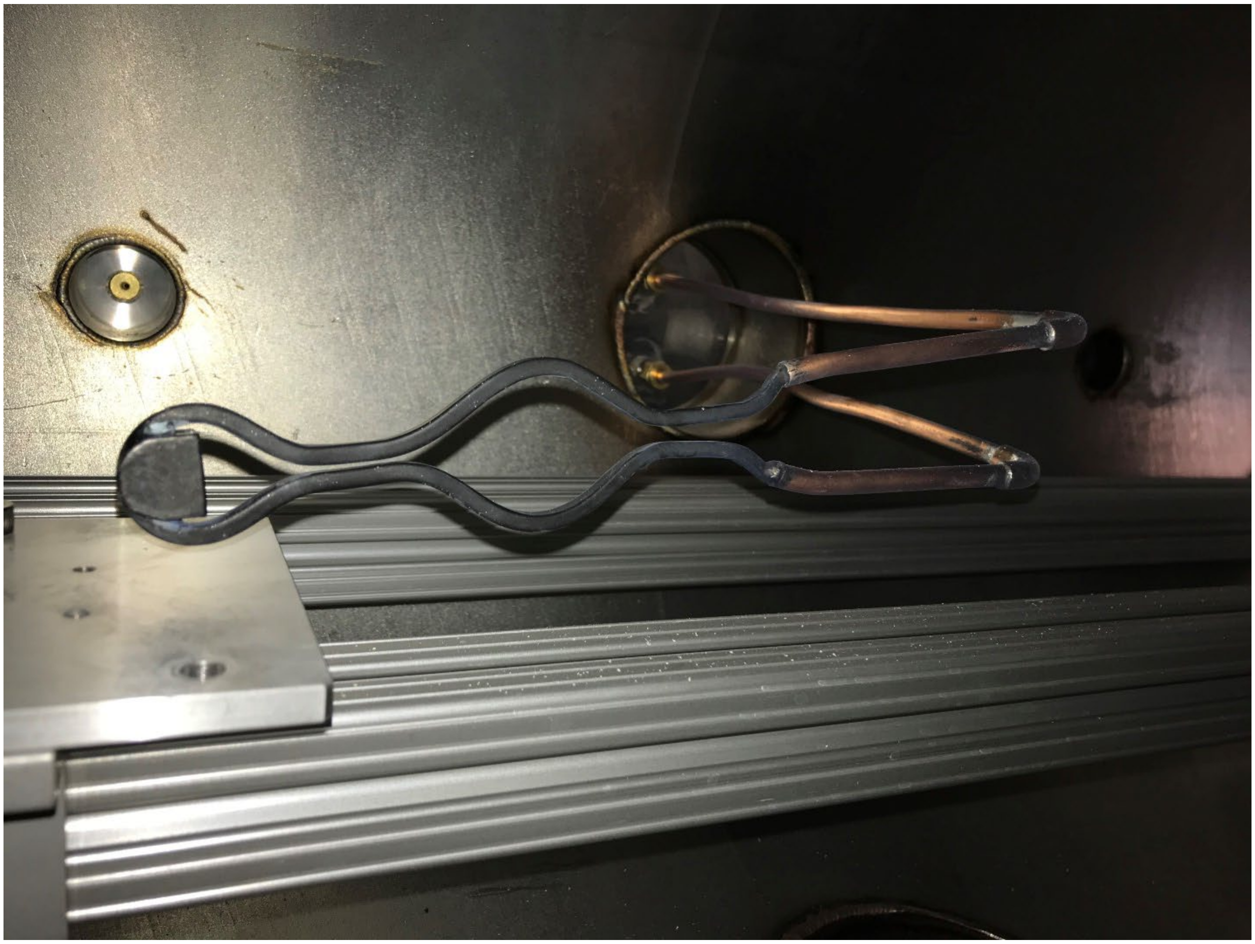

Figure 2 – Induction heater coil within pressure vessel

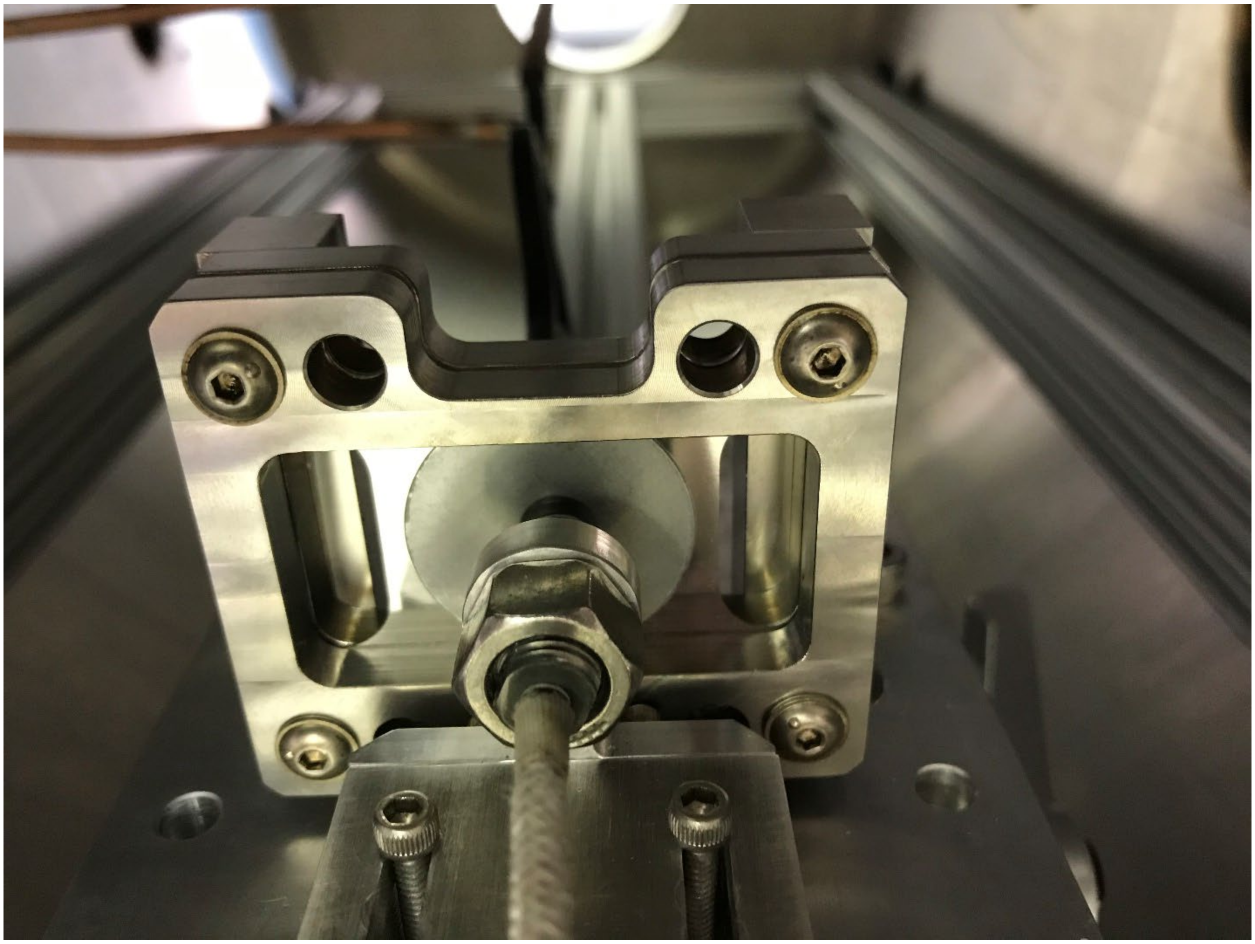

Figure 3 - Capacitec displacement sensor centered to Mo-100 disk

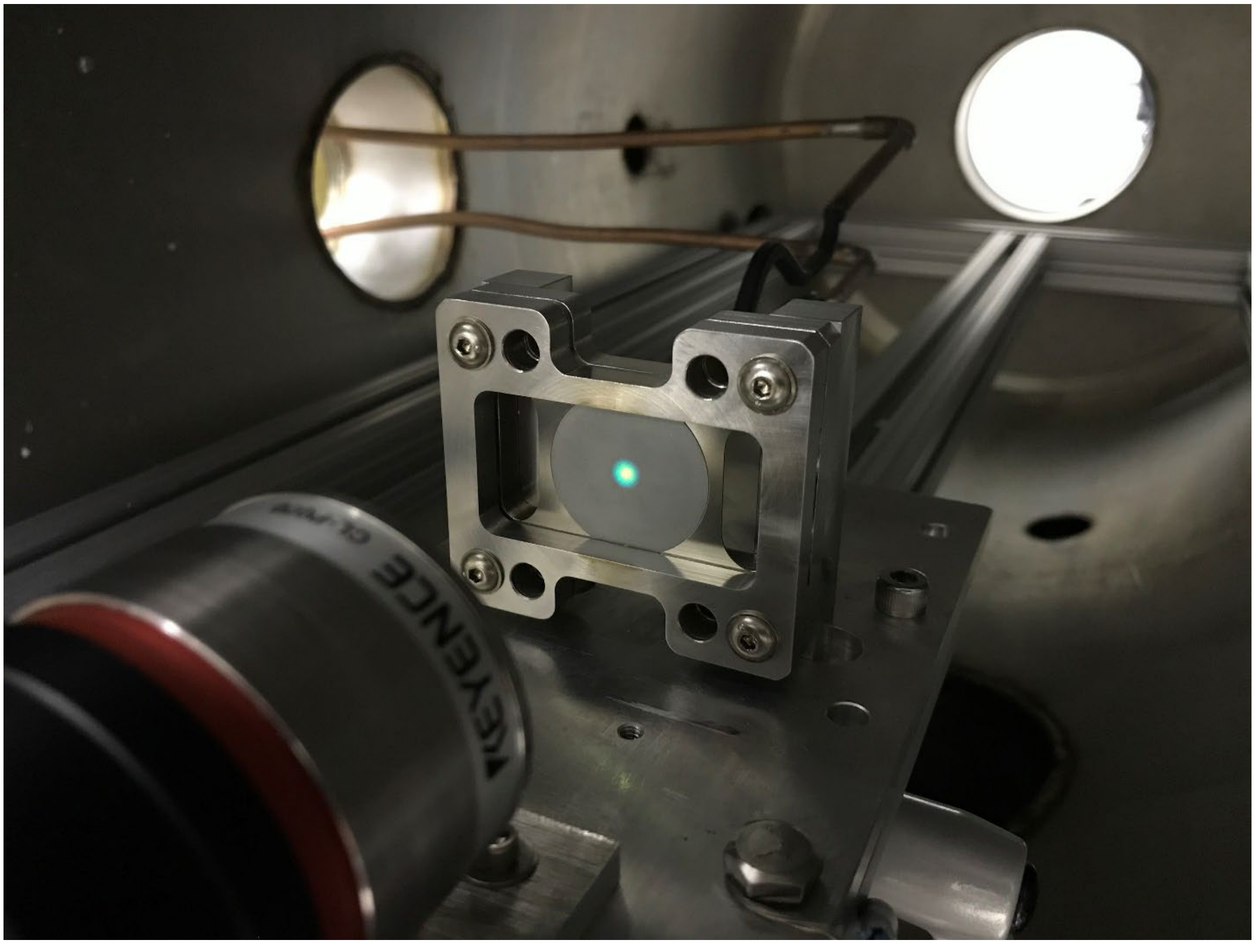

Figure 4 - Keyence confocal displacement sensor centered to Mo-100 disk

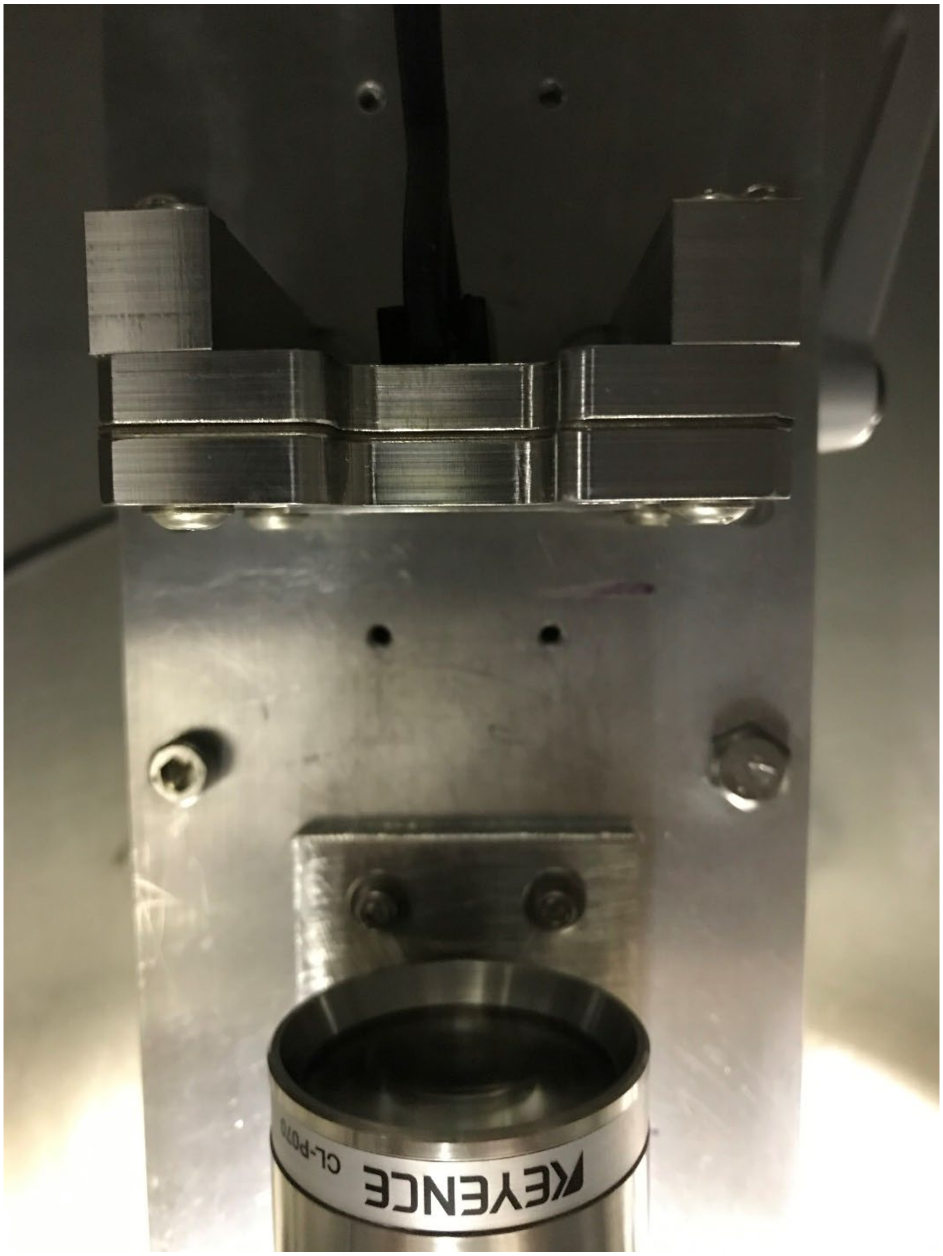

Figure 5 - Top down view of disk holder assembly, induction coil, and Keyence displacement sensor

The disk holder assembly, induction heater coil, and displacement sensor were contained in a pressure vessel with multiple feedthroughs and viewing windows. Prior to each disk thermal test, the pressure vessel was pumped down to rough vacuum (low mTorr range) and backfilled with helium to ~0.5 psig in order to prevent degredation of the molybdenum disk and provide cooling to the edges. Many tests have been performed to determine the proper pressure and flow of helium, and it was determined that no flow is required on the disk. Once at pressure, the induction heater was tuned for the current configuration, set to 80% power, and turned on. Once the desired temperature was reached by visual observation, the heater was manually turned off and the disk was allowed to cool (within seconds it was well below incandescent temperatures).

A FLIR ORX-10G-310S9C 31 MP color 10-Gig Ethernet camera paired with a Zeiss Milvus 2/135 lens was used to record still images of the incandescent disk during heating. The lens aperture was closed fully (F22) and the exposure was set to 12,583 within the FLIR software, Spinview. The disk began to emit yellow light (incandescence) within 4-6 seconds as it reached 1000°C at the center.

Results

Several tests were performed using various press and sintered at 1600°C natural and enriched Mo-100 disks provided by NorthStar. All but one series of tests were performed at maximum temperatures above 1000°C at the center of the disk. To date, the temperature has been monitored visually based on the incandescence of the disk. However, to confirm, a series of temperature tests were conducted using spot welded and surface contact .020" Type K thermocouples located at the center of a natural Mo-100 disk (210929-10). An NI Type K thermocouple module and Labview program was developed to record and display the temperature results. Unfortunately, the induction coil caused the thermocouple module to stop acquiring near the maximum temperature. A maximum temperature can be inferred from the slopes of the rising and decaying temperatures, but an OMEGA handheld thermocouple reader was used instead. The maximum temperature recorded for the .020" thermocouple in contact was 1019°C. However, the handheld thermocouple reader measured temperature at a much lower frequency than the NI module, so the actual temperature may have been higher. Figure 6 shows the incandescent hot spot while conducting a temperature measurement with a spot welded thermocouple. Figure 7 shows the hot spot using the FLIR camera and software, yet the image is still slightly overexposed. A properly exposed image is shown in Fig. 8, and this has been the temperature calibration standard for all tests.

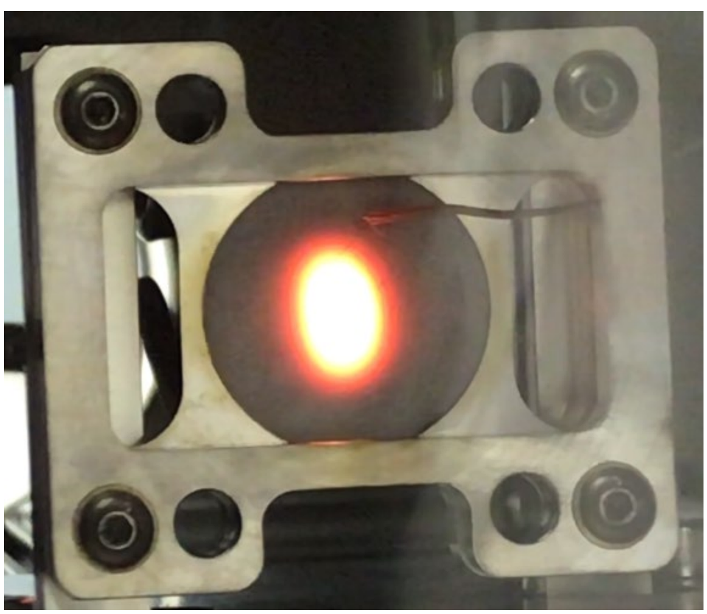

Figure 6 - Heat profile during thermocouple calibration test (iPhone 7, overexposed)

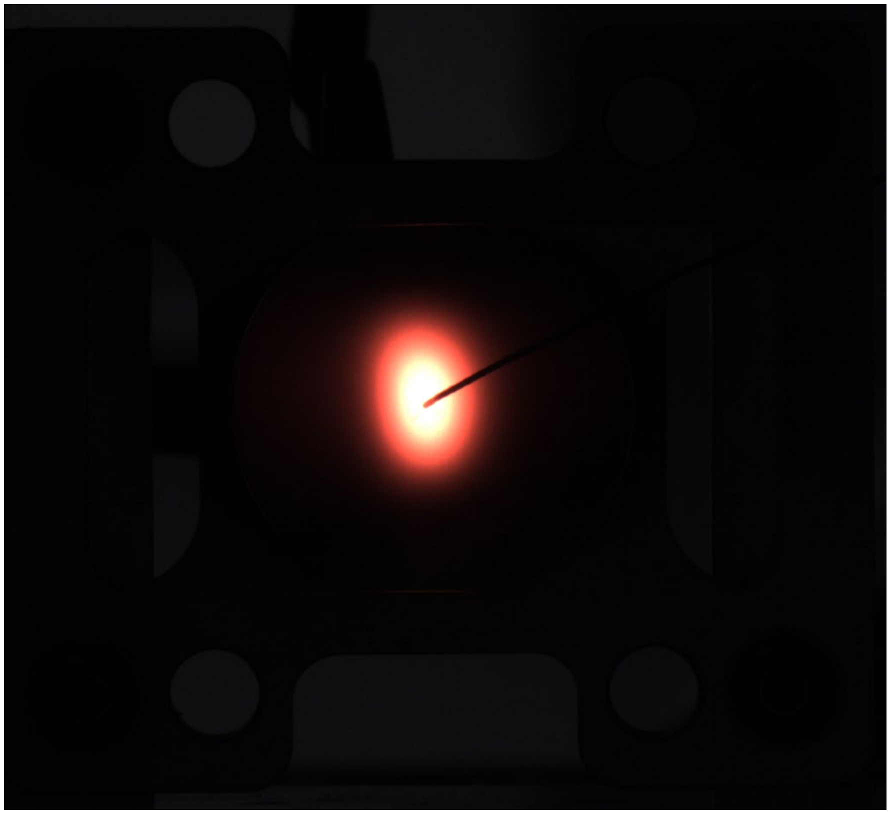

Figure 7 - .020” thermocouple in surface contact with Mo-100 disk

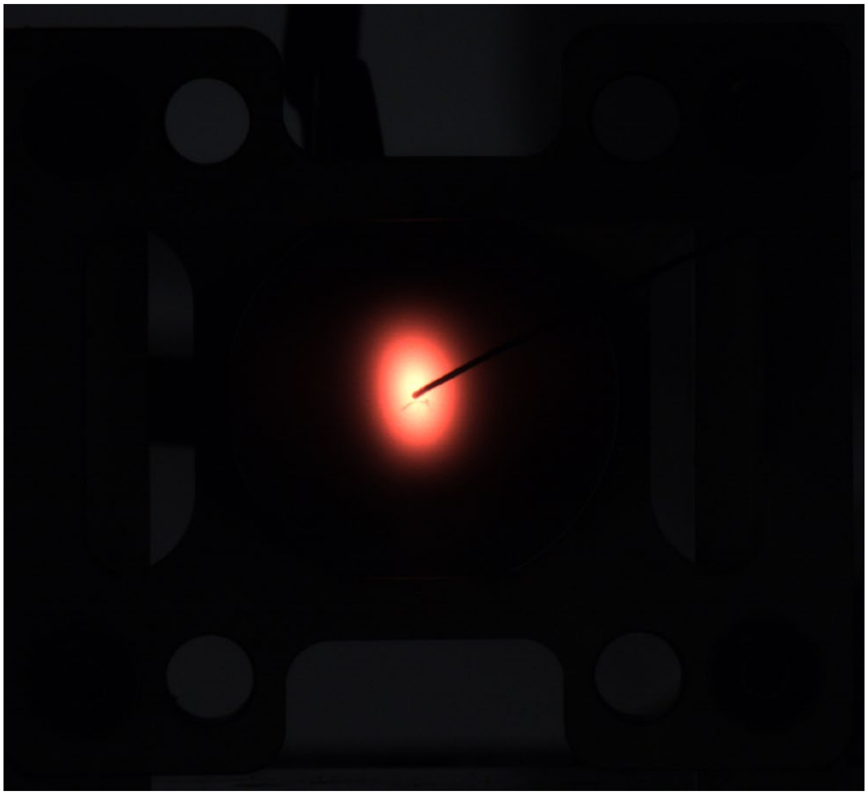

Figure 8 - Properly exposed hot spot

Table 1 shows the displacement results for the natural Mo-100 disk designated as 210929-23. The disk thickness was between .489-.507 mm (average is .500 mm), a height between .513-.526 mm (average is .520 mm), and a diameter between 29.14-29.24 mm. The disk was held tightly so that there was zero tolerance through the thickness of the holder and disk. The tolerance through the diameter of the disk was nominally .003" (.076 mm). A total of four tests were performed which gave an average displacement of .0101" (.256 mm). Note that the disk displaced away from the heater coil in all four tests.

Table 1: Natural Mo-100 Disk 210929-23 held tightly

Test	Displacement [inch]	Displacement [mm]
1	.0101	.256
2	.0100	.254
3	.0101	.256
4	.0101	.256
Avg	**.0101**	**.256**

Table 2 shows the displacement results for the enriched Mo-100 disk designated as 210831-3. The average disk thickness was .527 mm (micrometer) and a diameter of 28.18 mm (micrometer). The disk was held tightly so that there was zero tolerance through the thickness of the holder and disk. All four #8-32 screws were torqued to 18.5 in-lbs[2] which equates to a total force of 2256 lbf. The tolerance through the diameter of the disk was nominally .043" (1.08 mm). A total of five tests were performed which gave an average displacement of .0102" (.259 mm). The disk permanently deformed .0083" (0.21 mm). Note that the disk displaced towards the heater coil in all five tests. The transient results of displacement for all five tests can be seen in Figure 9. Notice that the rate of heating is slightly different for each test.

Table 2: Enriched Mo-100 Disk 210831-3 held tightly

Test	Displacement [inch]	Displacement [mm]
1	.0108	.274
2	.0114	.290
3	.0097	.246
4	.0098	.249
5	.0093	.236
Avg	**.0102**	**.259**

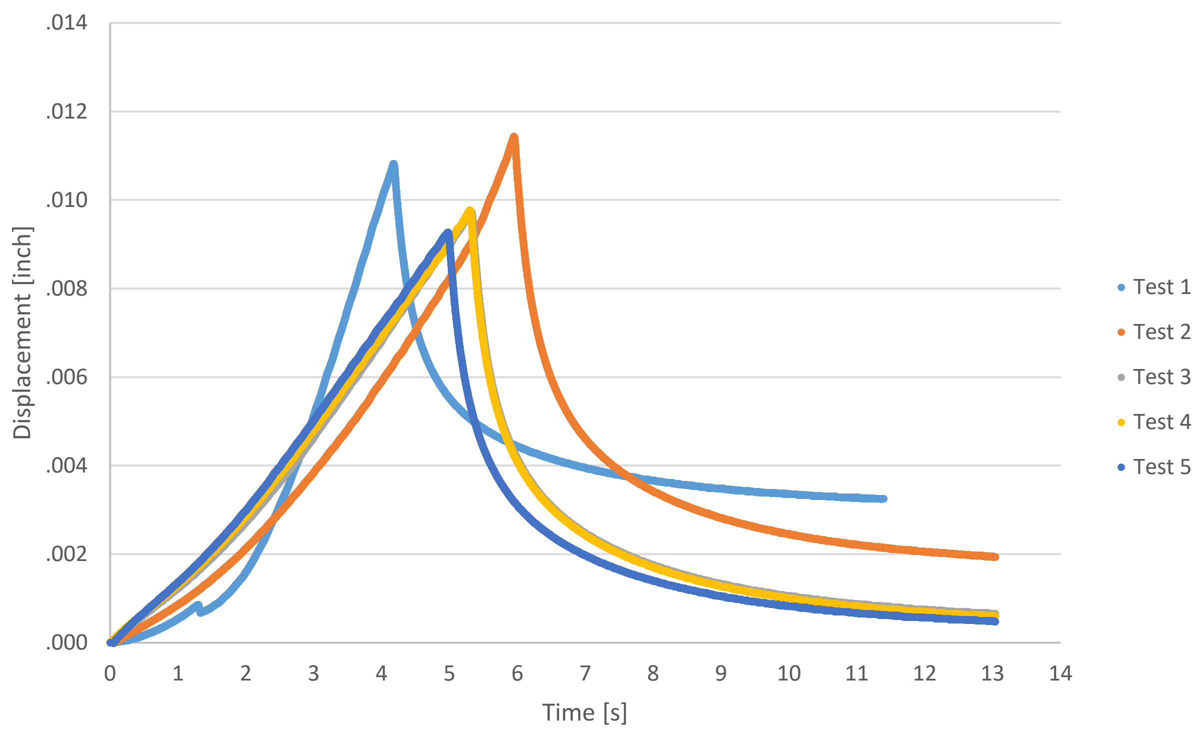

Figure 9 - Enriched Mo-100 disk 210831-3 displacement with time

Table 3 shows the displacement results for the enriched Mo-100 disk designated as 210831-4. The average disk thickness was .508 mm (micrometer) and a diameter of 28.45 mm (micrometer). The disk was held snug but allowed to move radially so it was estimated to have

[2] https://www.fastenal.com/content/merch_rules/images/fcom/content-library/Torque-Tension%20Reference%20Guide.pdf

a .0005” tolerance through the thickness of the holder and disk (backed by feeler gauge measurements). The tolerance through the diameter of the disk was nominally .032” (0.81 mm). A total of five tests were performed which gave an average displacement of .0034” (.086 mm). Note that the disk displaced away from the heater coil in all five tests.

Table 3: Enriched Mo-100 Disk 210831-4 “snug” fit

Test	Displacement [inch]	Displacement [mm]
1	.0032	.081
2	.0032	.081
3	.0028	.071
4	.0038	.097
5	.0040	.102
Avg	**.0034**	**.086**

Another series of tests was performed with the same enriched Mo-100 disk designated as 210831-4. This time, the disk was held tightly so that there was zero tolerance through the thickness of the holder and disk. All four #8-32 screws were torqued to 18.5 in-lbs which equates to a total force of 2256 lbf. Unfortunately, the maximum temperature was slightly lower than all previous tests and was estimated to be between 840-940°C[1] based on visual color. Table 4 shows the results of the five tests which gave an average displacement of .0127” (0.322 mm). Note that the disk also displaced away from the heater coil in all five tests.

Table 4: Enriched Mo-100 Disk 210831-4 held tightly

Test	Displacement [inch]	Displacement [mm]
1	.0123	.312
2	.0128	.325
3	.0131	.333
4	.0126	.320
5	.0125	.318
Avg	**.0127**	**.322**

The next series of tests were performed with a new enriched Mo-100 disk designated as 210831-5 that was held tightly so that there was zero tolerance through the thickness of the holder and disk. All four #8-32 screws were torqued to 5, 10, and 18.5 in-lbs which equates to a total force of 610, 1220, and 2256 lbf, respectively. The average disk thickness was .511 mm (micrometer) and a diameter of 28.41 mm (micrometer). The tolerance through the diameter of the disk was nominally .033” (0.85 mm). Table 5 shows the displacement results for each torque value. A total of five tests were performed for each torque value which gave an average displacement of .0063” (0.161 mm), .0163” (0.415 mm), and .0194” (0.493 mm), respectively. Note that the disk displaced towards the heater coil in all fifteen tests. By the end of these tests, the disk permanently deformed .028” (0.71 mm) in the direction of the heater coil.

Table 5: Enriched Mo-100 Disk 210831-5 torqued to 5 in-lbs

Test	Displacement [inch]	Displacement [mm]
1	.0061	.155
2	.0054	.137
3	.0063	.160
4	.0065	.165
5	.0074	.188
Avg	**.0063**	**.161**

Table 6: Enriched Mo-100 Disk 210831-5 torqued to 10 in-lbs

Test	Displacement [inch]	Displacement [mm]
6	.0139	.353
7	.0154	.391
8	.0157	.399
9	.0179	.455
10	.0187	.475
Avg	**.0163**	**.415**

Table 7: Enriched Mo-100 Disk 210831-5 torqued to 18.5 in-lbs

Test	Displacement [inch]	Displacement [mm]
11	.0196	.498
12	.0196	.498
13	.0193	.490
14	.0189	.480
15	.0196	.498
Avg	**.0194**	**.493**

Conclusion

All but one set of Mo-100 disk thermal tests were conducted with center temperatures >1000°C that were determined visually and verified by thermocouple measurements. The first two sets of tests using a tight fit, natural and enriched Mo-100 disk, resulted in nearly identical displacements of .010”. The third set of tests using a snug fit, enriched Mo-100 disk, displaced only .003”. The fourth set of tests using the same previously heated enriched Mo-100 disk, only with a tight fit and <1000°C, displaced .013”. The final set of tests using a new enriched Mo-100 disk with varying screw torque values of 5, 10, and 18.5 in-lbs, displaced .006”, .016”, and .019”, respectively. One can see that the maximum displacement of two new enriched Mo-100 disks under the same holder conditions had a difference of .009”. It is speculated that variation in disk material properties and increased heating cycles has caused this range of results, but further tests are required to confirm.

Although this sample size was small, it is evident that low disk clamping force and even a slight tolerance through the thickness of the disk and holder will significantly reduce the displacement of the disk during thermal loading. Additional tests are suggested to study effects of other parameters such as disk manufacturing variability and diameter tolerance between the disk and holder.